# LST User Exploitation Document

**A review of the applications of current satellite-derived Land Surface Temperature (LST) products and a synthesis of user requirements**

**ESA Contract Number: 19054/05/NL/FF**

**Issue 1A**


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# Summary

This report describes the work carried out at the University of Leicester within the framework of Work Package 610 of the ESA project “Long Term Land Surface Temperature Validation”. Work Package 610, titled “User Interaction” concerns the promotion of AATSR LST data, and the liaison with users and other researchers working in the field of satellite LST to increase publicity and user exploitation. This document summarises the user requirements for LST.

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## 1. Introduction

Land surface temperature (LST) is the mean radiative skin temperature of an area of land resulting from the mean balance of solar heating and land-atmosphere cooling fluxes. It is a basic determinant of the terrestrial thermal behaviour, as it controls the effective radiating temperature of the Earth's surface. It determines the surface air temperature and the long-wave radiation between the surface and the atmosphere, and is influenced by various surface-atmosphere boundary conditions, such as precipitation and albedo (Huang *et al.*, 2008). In addition it influences the partitioning of energy into ground, sensible (Sun and Mahrt, 1995), and latent (Sellers *et al.*, 1997) heat fluxes. What is more, LST is distinct from air temperature, with LST being more closely related to the physiological activities of leaves (Sims *et al.*, 2008) in vegetated areas, and to soil moisture in sparsely vegetated areas. Indeed, differences between simultaneous measurements of LST and air temperature can be as a much as 20 K for (Byrne, 1979). LST has a strong diurnal variation and strong heterogeneity with spatial distances imposed by biome variations; values can vary by as much as 10 K over just a few metres (Prata, 1994).

The sensitivity of LST to soil moisture and vegetation cover means it is an important component in numerous applications (section 3). For instance, LST is a key boundary condition in land surface models (Kustas and Norman, 1996), which determine the surface to atmosphere fluxes of heat, water and carbon; thus influencing cloud cover, precipitation and atmospheric chemistry predictions within General Circulation Models. Changes in land-surface cover can affect global climate, and can be identified by changes in their surface temperatures. Tropical deforestation, for example, results in the land experiencing a reduction in evapotranspiration. This reduction in cooling potential increases the surface temperature (Betts, 2001), with dry soil, or vegetation under stress due to a lack of moisture availability, being warmer than wet soil, or vegetation which is not moisture limited.

Satellite-derived LST products can be used to improve our ability to monitor and to understand land surface changes, such as desertification, urbanization and deforestation. A suite of sensors (section 2) onboard polar-orbiting and geostationary satellites, which measure emitted radiation, enables LST to be retrieved globally for different spatial and temporal resolutions. This data is utilized by groups and individuals from a range of disciplines studying diverse applications of LST, such as urban climate change and geothermal anomalies. Here we summarize the data requirements of these users as ascertained from previous reports and workshops (section 4) and present the findings of a recent survey (section 5).

## 2. Earth Observation of LST

### 2.1. Summary

Remote sensing of LST is based on total radiative energy emitted by the ground surface increasing with temperature. Land surface radiometric temperature can be determined from satellite measurements of thermal emission at either infrared or microwave wavelengths. Due to the larger range of variation in surface emissivities uncertainties in microwave retrievals can be large relative to thermal infrared (TIR) retrievals of LST; the latter have a stronger dependence of the radiance on temperature. However, measurements in the TIR are much more sensitive to cloud contamination than are microwave measurements. Indeed, because of the requirement for cloud detection this can limit the spatial and temporal sampling of TIR measurements.

Instruments aboard Earth Observation (EO) satellites which measure top-of-atmosphere (TOA) radiances to TIR combine the upwelling radiance emitted by the atmosphere, the upwelling radiance emitted by the ground, and the downwelling radiance emitted by the atmosphere and reflected by the ground. The accuracy of these LST retrievals however, can be difficult to achieve, due to emissivity variability; and the effects of the atmosphere. Most LST algorithms usually operate in the 8-13μm TIR range where atmospheric absorption is minimized (Dash *et al.* 2002). Even so, water vapour absorption, and aerosols still cause significant atmospheric attenuation in this window of high transmission. The generalized split-window algorithms approach this problem by solving two simultaneous equations for TOA brightness temperatures - one for each channel usually at approximately 11μm and 12μm - since atmospheric attenuation is a function of the differential absorption at each channel wavelength (Trigo *et al*., 2008a).

For most scenes the ground is not a homogeneous surface, which increases the challenge of measuring the surface temperature. For bare soil surfaces LST is the temperature of the surface of the soil. Where the ground is densely covered with vegetation LST can be viewed as the canopy surface temperature. In mixed scenes of vegetation and bare ground, LST is the average temperature of the canopy, vegetation body and the surface of the bare soil. Strong heterogeneity within the landscape means LST can vary significantly at sub-pixel scales. As the spatial resolution of most remotely sensed LST products is coarse in comparison with the

LST heterogeneity on the ground, the LST retrieved from EO satellites is an aggregation of the mean surface temperatures of the different fractions of surface types.

### *2.2. LST products*

LST can be acquired from thermal infrared sensors, which have the advantage of higher radiometric accuracy; and passive microwave radiometers, which can penetrate cloud. Here though, only the four most widely used thermal infrared sensors will be summarized.

The Advanced Along-Track Scanning Radiometer (AATSR) on board the sun-synchronous, polar orbiting satellite Envisat is part of the ATSR family (ATSR-1 on board ERS-1, ATSR-2 on board ERS-2), which can provide nearly 20 years worth of data. AATSR is able to provide observations from two viewing angles, nadir and forward; however, only the nadir view is utilised in the LST retrieval. With a swath width of 512km, AATSR is able to provide approximately 3-day global LST coverage with a repeat cycle of 35 days. The product has good radiometric accuracy of less than 0.1 K with on board calibration. The target accuracy is 2.5 K during the day, and 1 K at night (Llewellyn-Jones *et al.*, 2001). A nadir-only split-window algorithm is utilised in which 1km LST is retrieved based on the infrared (IR) channels at 11 and 12µm, whereby regression coefficients depend on fraction of vegetation cover, precipitable water, thirteen land cover classes and one lake class (Prata, 1993; Prata, 1994). The accuracy of AATSR observations reported by Coll *et al*. (2005) is better than 0.9 K.

MODerate resolution Imaging Spectroradiometer (MODIS) 1km LST is acquired from TIR sensors on board the sun-synchronous, near-polar orbiting satellites Terra and Aqua. As a result of the large swath width of 2330km, each satellite provides almost total global coverage each day. For MODIS on Terra two LST retrievals can be obtained each day corresponding to approximately 10:30am local solar time in its descending mode; and approximately 10:30pm local solar time in its ascending mode. For MODIS on Aqua LST retrievals are approximately 1:30am/pm local solar time. This allows the daily temperature difference to be captured. A generalized split-window algorithm (Wan and Dozier, 1996) is used to estimate LST as a linear function of clear-sky TOA brightness temperatures from bands 31 and 32 centred on 11µm and 12µm respectively, with surface emissivity estimated from land cover types. The reported accuracy is better than 1.0 K (Wan *et al*., 2002; Wan *et al*., 2004b; Wan, 2008).

The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument on board the Meteosat Second Generation (MSG) geostationary satellites centred over the equator retrieves an image every 15 minutes, with a pixel size between 3km and 5km. The approximate altitude of 36000km means higher zenith angles than the polar-orbiting satellites. This increases the difficulty of retrieval due to increased atmospheric attenuation. The larger pixel size, which increases with viewing angle, means observations are more difficult to validate with ground measurements. The higher temporal frequency though does enable the diurnal cycle of LST to be captured. A generalised spilt-window algorithm using TOA brightness temperatures for channels 10.8μm and 12.0μm is used to process LST data, using fraction of vegetation cover to estimate surface emissivity (Trigo *et al.*, 2008b). For most simulations between nadir and 50° viewing zenith angle, the reported LST accuracy is 1.5 K (Sobrino and Romaguera, 2004).

Finally, the Advanced Very High Resolution Radiometers (AVHRR) on board NOAA's polar orbiting satellites can retrieve 1km LST twice daily using the split-window method of Becker and Li (1990). It can capture the daily temperature difference with daytime overpasses occurring during the period of maximum surface/air temperature, approximately 13:00 to 14:00 local time; and night overpasses occurring during the period of minimum surface/air temperature, approximately 02:00 to 03:00 local time. An advantage of this dataset is that it has a relatively long data record of more than 20 years, and is thus widely used in applications.

# 3. LST applications

## *3.1. Climate change*

Both the full LST diurnal cycle and the daily temperature difference between day and night are important components in the climate system, being representative of key surface properties such as soil moisture content and thermal inertia. What is more, long-term trends in surface temperature are key characteristics in identifying climate change. While both MODIS and AVHRR can provide a measure of the daily temperature difference, the full diurnal cycle cannot be directly obtained from these polar orbiting satellites. The strong variability of the LST diurnal cycle means polar-orbiting satellites which measure the same surface periodically separated by hours or days are limited in their potential to observe the whole diurnal cycle. Indeed, cloudy scenes limit the potential even further. SEVIRI and other geostationary sensors can capture this diurnal cycle, albeit over regional areas of the Earth's surface, due to the high temporal resolution of their retrievals. However, with the disadvantages highlighted in section 2.2, potential exists for combining these retrievals with those from polar-orbiting sensors in order to generate a high-spatial resolution, high-temporal resolution LST data set, which would be important for climate change studies.

More specifically, LST retrieved from EO satellites can be used to monitor urban climate, both in obtaining boundary conditions of the atmosphere, but also in understanding the environmental conditions necessary to sustain human life. Urbanization causes the local air and surface temperature to rise several degrees higher than the temperatures of the surrounding rural areas creating what is known as the urban heat island (UHI) effect. The main contributing factors are changes in the physical characteristics of the surface, such as thermal capacity, heat conductivity, and albedo. This is due to the replacement of vegetation by man-made material decreasing, for example, the cooling effect of evapotranspiration (Dousset and Gourmelon, 2003).

Research on urban surface energy includes, for example, the study by Pongracz *et al*. (2006) who used day and night MODIS surface temperature to determine UHI intensities over the ten most populated cities of Hungary. Hung *et al*. (2006) analyzed the UHI in eighteen Asian mega cities using cloud free, day and night MODIS LST acquired from Terra between 2001 and 2003. Dousset and Gourmelon (2003) analyzed spatial and temporal variations of urban LSTs and land cover using combined vegetation indices and AVHRR LST data to show that urban surface properties, such as vegetated areas, water, and built-up areas affected the UHI intensity. Furthermore, during heat waves LSTs were found to correspond with elevated LSTs during the night; the spatial distribution of the highest LSTs were well correlated with the highest mortality rates during these heat waves (Dousset *et al.*, 2010). Finally, ESA is funding an Urban Heat Island and Urban Thermography (UHI) project under the Data User Element (DUE) program; more information can be found at http://www.urbanheatisland.info/.

### 3.2. *Land/atmosphere feedbacks*

Anthropogenic climate changes, such as increased surface temperature, and changes in precipitation and net radiative heating influence the state of the land surface in terms of soil moisture, albedo and roughness. Theses changes to the land surface in turn drive important feedbacks to the atmosphere. LST plays an important role in the energy balance of the Earth, being a determining factor in the partitioning of available energy into sensible and latent heat fluxes, and heat flux into the ground. More energy is partitioned into latent heat for higher vegetative cover, whereas higher sensible heat is more typical of sparsely vegetated surfaces. Because water vapour transports energy to the atmosphere, latent heat flux is positively related to evapotranspiration. This constitutes an important climate system feedback between the land-surface and the atmosphere because soil moisture anomalies can translate into precipitation anomalies through the evapotranspiration rate (Shukla and Mintz 1982). This feedback on the precipitation regime could influence the occurrence and persistence of pluvial and drought conditions. This in turn influences the distribution of vegetation, thereby altering surface albedo and subsequent surface evaporation.

Numerous studies have utilized LST data from EO satellites to estimate feedbacks between the land and the atmosphere. Xue *et al*. (1997) for example, developed a model to obtain long-wave radiation, short-wave irradiation, sensible heat flux and latent heat flux at Earth's surface from the ATSR-1 thermal band data and the ATSR-2 visible and thermal band data. Bisht *et al*. (2005) used MODIS LST data from Terra, in combination with land surface emissivity, surface albedo, and air temperature data to estimate the net radiation over large heterogeneous areas of the Southern Great Plains in the USA for clear sky days.

To illustrate the importance of accurate LST retrievals from satellite in estimating land-atmosphere feedbacks, Brutsaert *et al*. (1993) reports a 10% error in sensible heat flux as a result of a 0.5 K uncertainty in LST. If the uncertainty in LST is 1.0 K then Moran and Jackson (1991) suggest an associated uncertainty in evapotranspiration of 10%. Finally, Kustas and Norman (1996) suggest a LST error of 1.0 K to 3.0 K can lead to errors of up to $100Wm^{-2}$ in surface-to-atmosphere heat fluxes. It is clear from these studies that the feedbacks between the land surface and the atmosphere are highly sensitive to the surface temperature.

## *3.3. Modelling studies*

LST is an important component of the surface energy budget, and is thus of significant value in validating and constraining global and regional climate models because of its relevance to the computations of terrestrial radiation and turbulent heat fluxes. Model parameterization affects the surface temperature generated in models, with each model having its own unique set of parameters which need to be validated. A common use of satellite-derived LST data has been in the validation / calibration of other remotely sensed LST data sets (Noyes *et al.*, 2006; Trigo *et al.*, 2008a). However, the importance of surface temperature in land surface modelling has driven much recent work using LST data sets to validate the output of models (Jin *et al.*, 1997; Rhoads *et al.*, 2001; Ge *et al.*, 2008) and to constrain their parameterizations (Margulis and Entekhabi, 2003; Bosilovich *et al.*, 2007). With its strong diurnal cycle, utilisation of LST in models means a requirement for sub-daily observations. EO satellites represent the most practical source over large geographical areas.

Comparisons of satellite-derived LST with model estimations can provide a valuable insight into the performance of the current LST products and improve the accuracy of both EO and model predictions. While parameterizations affect the simulated data, the forcing data is equally important. For example, there are wide variations in the amount and properties of clouds produced in models, which affect LST. Such uncertainties in the simulations of LST can feedback into the partitioning into sensible and latent fluxes. This can lead to large differences between the model simulations of LST and remotely sensed observations.

High quality observations can provide a constraint on these model simulations with the aim of reducing uncertainty. As such there has been much recent interest in integrating satellite observations into climate models, which can take advantage of the strengths of both satellite observations and model predictions. This technique is known as data assimilation, whereby the correction applied to the model is derived from the respective weightings of the uncertainties of both the model predictions and the observations. With LST being integral to the surface energy budget it is one of the most promising choices for constraining models. Indeed, LST products have been extensively used as inputs into assimilation routines to help improve the estimate of model state and prognostic variables. These are in turn used to improve the understanding and quantifications of surface fluxes, and water availability. For example, the impact on quantities such as latent heat flux can result in changes to the hydrological simulations in models. Numerous examples (Margulis and Entekhabi, 2003; Huang *et al.*, 2008; Pipunic *et al.*, 2008) exist of reduced uncertainty as a result of the assimilation of satellite-derived LST into models; although these have often been limited to experiments with relatively simple biophysical models over local areas. Assimilation of LST into land surface models enable improved representations of key surface to atmosphere fluxes of heat and moisture, thus influencing the land-atmosphere coupling (Ghent *et al.*, 2010; Ghent *et al.*, 2011).

While LST assimilation has been studied for many years, there still exist numerous limitations in implementing such data assimilation schemes to the best possible capability. An underlying assumption of data assimilation is that the differences between the model and observation are not biased. However, systematic biases often exist due to uncertainties among EO products as a result of variable observation angles and cloud contamination, and due to the fact that land surface heterogeneity in models is at best parameterized. Furthermore, there may be diurnal components to these LST biases, so to minimize uncertainty LST data assimilation may require observations that resolve the diurnal cycle. A data assimilation scheme must take account of these uncertainties as a matter of course. Although early breakthroughs have been made, broad global use of the integration of satellite-derived LST observations into climate models still faces the challenges outlined above.

### *3.4. Land cover change*

The partitioning of sensible and latent heat fluxes is a function of varying soil moisture and vegetation cover (Owen *et al.*, 1998). For instance, higher latent heat exchange is associated more with vegetated areas, whereas higher sensible heat exchange corresponds more with areas that are sparsely vegetated, such as deserts and urban areas. Any change in the land cover of the Earth’s surface will inevitably result in a change to the soil moisture and surface albedo, which are two of the most significant determining factors in LST variability (Goward *et al.*, 2002). Surface albedo determines the amount of energy absorbed by the land surface, and thus is available for partitioning into sensible and latent heat fluxes. Soil moisture also has a significant influence on this partitioning; a wet soil surface for instance is cooler and loses more latent heat, whereas a dry soil surface loses more sensible heat and generally corresponds to higher surface temperatures (Smith *et al.*, 2006). Because of its sensitivity to soil moisture and vegetation cover LST is important in applications such as desertification, land cover mapping and change detection. Furthermore, LST data can be used in mapping burned area, which will be described in more detail in section 3.7.

Sobrino and Raissouni (2000) demonstrated that AVHRR LST and Normalized Difference Vegetation Index (NDVI) data also from AVHRR could be used to monitor desertification. In their study in Morocco, two methods were analysed: one based on a description of the evolution of the NDVI and LST over an annual period; and one which analysed the slope of the line defined by the months of the maximum NDVI and the minimum LST. Their findings indicated that the area undergoing desertification corresponded with low NDVI and high LST.

Amidst the growing demand for land cover mapping at both global and regional scales, some studies have reported that vegetation indices, such as NDVI, could not provide sufficient information for land cover mapping as a result of the influence of soil moisture and its physical properties, and surface temperature (Dobos *et al.*, 2000; Yang *et al.*, 1997); whereas vegetation indices containing data acquired in the middle infrared and TIR channels performed better (Foody, *et al.*, 1996).

Indeed, data acquired in the thermal bands can be useful for land cover change detection, as reported by Ehrilich *et al*. (1994) in their study of tropical forests. Lambin and Ehrlich (1997) also applied a change index based on remotely sensed surface temperature and vegetation indices to study continental interannual land cover change in Africa from 1982 to 1991. Their findings demonstrate that erratic variations in land-cover conditions due to interannual climatic variability and temporary modifications in seasonality were primarily responsible for land cover changes in Africa during these years.

## 3.5. *Crop management*

The use of LST to monitor water stress in plants, and hence its application in crop management, is based upon the relationship between canopy temperature and transpiration. In other words, as a plant transpires the leaves cool so that the surface temperature of the canopy is lower than the surrounding air temperature. If water is limiting and transpiration is decreased, then as the leaves absorb radiation the surface temperature of the canopy increases above the surrounding air temperature.

The use of remote sensing data, including LST, has proved to be important in several aspects of crop management, such as stress detection, monitoring crop growth, forecasting yield, and in irrigation scheduling. For example, Prasad *et al*. (2006) used remotely sensed surface parameters to estimate crop yield over the state of Iowa in the USA for a period of nineteen years from 1982 to 2001. In their study, annual means of soil moisture, surface temperature, NDVI data and precipitation were analyzed. They were able to forecast crop yields of corn, soybeans and other crops with acceptable accuracy.

Other methods include the monitoring of crop water use in irrigated areas by utilizing a surface energy balance method (Bastiaanssen *et al.*, 1998; Allen *et al.*, 2005). The approach taken requires solving the surface energy balance equation to derive actual evapotranspiration from the latent heat flux, the latter being the difference between the net radiation and the fluxes of sensible heat and the heat into the ground.

The most established method though to monitor crop water stress remotely is through the derivation of a crop water stress index (CWSI), which correlates to crop yield and soil water availability and can be applied in irrigation scheduling. A first CWSI was calculated, for a particular vapour pressure deficit, as the ratio of the difference between the measured canopy temperature and its lower limit, against the difference between the maximum and minimum canopy temperature (Idso *et al.*, 1981). This method was enhanced (Jackson *et al.*, 1981; Jackson *et al.*, 1988) by the addition of an estimate of net radiation and an aerodynamic resistance factor. A CWSI varies between 0 and 1 with 0 representing a plant transpiring at the maximum rate, and 1 representing a plant having no transpiring loss.

### 3.6. *Water management*

As has been demonstrated in section 3.5, LST is important in applications such as vegetation water stress monitoring, as a result of its close relationship to vapour pressure deficit (Hashimoto *et al.*, 2008) and surface energy balance assessment (Pinheiro *et al.*, 2006). Moreover, the use of remotely sensed TIR data is a valuable indicator of the surface moisture and evapotranspiration. For example, Wan *et al*. (2004a) used LST and NDVI, both from MODIS, to monitor drought in the southern Great Plains of the USA. In the study by Anderson *et al*. (2007), TIR imagery from the Geostationary Operational Environmental Satellites (GOES), vegetation data from MODIS, and an atmosphere-land exchange model were used to map daily evapotranspiration and surface moisture stress over a 10km resolution grid covering the continental United States. In their findings, monthly anomalies of moisture stress showed good spatiotemporal correspondence with patterns of antecedent precipitation, and with standard drought metrics. Furthermore, studies of LST anomalies identifying relatively wet and dry surfaces have identified Plantetary Boundary Layer gradients in thermodynamic properties (Taylor *et al.*, 2007; Taylor *et al.*, 2010).

Soil moisture availability can be assessed by using LST data to derive a property known as thermal inertia (TI), which describes the resistance of a property to temperature variations based on its material density, thermal conductivity, and specific heat. Water bodies have a higher TI than dry soil, and exhibit a lower diurnal temperature fluctuation. This fluctuation range is reduced when water content of soils increases, with their TI increasing proportionately. Although TI can be derived from the temperature diffusion equation, a simpler formulation is the apparent thermal inertia (ATI) which can be derived directly from remote sensing imagery. For example, Mitra and Majumdar (2004) derived ATI from satellite-based surface albedo and the diurnal range of LST. Maximum and minimum ATI values derived from EO data can be combined in a Soil Moisture Saturation Index (SMSI), which is based on the ratio of the difference between the derived thermal inertia and the minimum thermal inertia, and the difference between maximum and minimum. Verstraeten *et al*. (2006) applied this methodology using optical and thermal data from METEOSAT imagery to derive soil moisture content. Their results showed reasonable accuracy when validated against observations from ten EUROFLUX sites in Europe during March to October 1997.

In addition to monitoring vegetation water stress, and deriving soil moisture, remotely sensed LST products can be utilized for a multitude of water management applications: the assessment of agricultural and urban water consumption; the negotiation and monitoring of water rights; the assessment of water losses from riparian systems and reservoirs; the assessment of aquifer depletion rates; the monitoring of sediment transport within rivers and into estuaries; and the assessment of water quality and alternative water management practices.

### *3.7. Fire monitoring*

The emissions from biomass burning contribute significantly to the quantities of $CO_2$ and trace gases in the atmosphere. Fire also plays an important role in land cover change processes such as deforestation. It is thus important to monitor the land surface that is burned on both regional and global scales. Thermal instruments can be used to monitor the high temperatures of active fires; with satellite-derived LST also having an important role to play in monitoring the fire regime, in applications such as burned area mapping and fuel moisture derivation.

LST data from ATSR-2, AVHRR and MODIS have been widely used for mapping burned area, showing good accuracy. The theory behind this application is based on charcoal and ash absorbing more energy than vegetation. This together with the loss of cooling from transpiring vegetation and reduction in soil moisture, at least in the short-term after fire, means that burned areas tend to have higher temperatures than the surrounding vegetation cover that was not affected. As an example, in their study over Africa, Barbosa *et al*. (1999) used different sets of AVHRR channels to derive burnt area indices; their results showed good agreement with known temporal and spatial patterns of active fires. In the study by Chuvieco *et al*. (2005) using AVHRR and MODIS imagery over the Iberian Peninsula in 2001, 2003 and 2004, they showed that their criteria - based on maximizing surface temperatures alone, or in conjunction with minimizing sensor zenith angle or near infrared reflectance - provided the most accurate images for burned area mapping.

Another fire detection application is the estimation of live fuel moisture content (FMC), which is considered one of the most important variables in fire occurrence, propagation, and fire risk monitoring (Chuvieco *et al.*, 2004; Verbesselt *et al.*, 2006); and is defined as the ratio between as the percentage of water weight over sample dry weight. In live vegetation FMC is mainly driven by plant physiology and soil moisture (Chuvieco *et al.*, 2004). The water content of fuels is inversely related to the probability of ignition and propagation, since part of the energy necessary to start a fire, and ignite adjacent fuels respectively, is used to evaporate water (Chuvieco *et al.*, 2002). Although good correlations have been reported between NDVI data and FMC for herbaceous species, this has not been the case for shrubs and trees (Chuvieco et al., 1999). Recent studies have experimented with the combined use of LST and NDVI, with these showing statistically stronger correlations with FMC than either of the two variables alone (Sandholt *et al.*, 2002; Chuvieco *et al.*, 2004; Chuvieco *et al.*, 2005). For example, Chuvieco *et al*. (2004) presented an empirical method for deriving FMC for Mediterranean grasslands and shrub species based on multi-temporal composites of NDVI and surface temperature from AVHRR, with the addition of a day-of-the-year factor. Their results showed strong correlations with FMC for all study sites and vegetation types, in which low NDVI values and high surface temperature were associated with low values of FMC.

## *3.8. Geological applications*

The use of thermal imagery from EO is unique in contributing to the identification of surface materials and features such as geothermal anomalies, and rock types (Prakash, 2000). Other geological applications of satellite-derived LST include: earthquake precursor detection and monitoring; detection and monitoring of the onset and progression of volcanic activity, including airborne volcanic ash plumes and low temperature thermal anomalies; aquatic thermal plume detection, associated for example with shallow undersea volcanic eruptions; differentiation of rock lithologies, which can be important for mineral exploration and geotechnical engineering; and geothermal resource exploration.

For instance, it has been suggested (Ouzounov and Freund, 2004; Tronin *et al.*, 2004) that thermal anomalies of LST are related to earthquakes and pre-seismic activities. In this first study, mid-infrared emission prior to strong earthquakes was analyzed using LST from MODIS and IR emissivity data. In their case study of the magnitude 7.7 Bhuj earthquake in Gujarat, India they found an anomalous LST of between 3 and 4°C consistent with similar reports from around the world. Their conclusion was that the rapid time-dependent evolution of the "thermal anomaly" makes it plausible that its cause was changing mid-IR emissivity from the ground. Furthermore, in the magnitude 7.2 Bougainville Isle seaquake an anomalously low sea surface temperature, due to cold water upwelling, was observed prior to the event; this they concluded, may have been caused by energy deposited into the ocean floor.

Infrared radiance data from EO satellites can be used for documenting remote effusive volcanic activity (Rothery *et al.*, 1988). The 1.6μm shortwave infrared waveband on the ATSR series of sensors is close to the wavelength of peak spectral radiant emittance for surfaces at magmatic and near magmatic temperatures making it useful for thermal studies of active lava. For example, in their study of the 1995 eruption of Fernandina Volcano, Wooster and Rothery (1997) used ATSR night-time images to estimate the flow of lava; with their estimates being similar in magnitude to previous studies.

### *3.9. Other applications*

In addition to the various applications highlighted above, there are number of minor research interests where satellite-derived LST data has been used. For example, LST data in conjunction with other satellite data such as land cover or vegetation indices is useful in studying the global or regional emissions of volatile organic compounds (VOCs), such as isoprenes, terpenes and monoterpenes. The controlling parameters for the VOC emissions are temperature and light intensity together with the species of plants and their distribution. In their study from the Amazonian rainforest, Rinne *et al*. (2002) found that isoprene flux correlated with a light- and temperature-dependent emission activity factor, and even better with measured sensible heat flux. Greenberg *et al*. (1999) also reported that day-time biogenic emissions increase with temperature and light, but appear to be balanced by changes in entrainment and oxidation. Finally, Guenther *et al*. (1991) reported that terpene emissions from conifers demonstrate an exponential increase with increasing temperature. Indeed, many biogenic emissions are highly temperature dependent (Duhl *et al*., 2008).

A final application is that remotely sensed LST data can be used in the identification of areas of atmospheric instability, when combined with meteorological and atmospheric data. As temperature increases so does atmospheric instability, which increases the likelihood of storms. A characteristic known as Convective Available Potential Energy (CAPE) is a measure of the amount of energy available for convection, and is directly related to the maximum potential vertical speed within an updraft. Higher values of CAPE indicate a greater potential for severe weather. In their study of CAPE, López et al. (2001) found a linear relationship - corresponding to the highest correlation - between the potential temperature for hail days and the measure of CAPE.

# 4. Synthesis of past findings

## *4.1. NCDC Workshop*

A previous workshop – the "International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps" – held at NOAA's National Climatic Data Center (NCDC) in the US in April 2008, co-sponsored by the GEWEX Radiation Panel and NASA, attempted to understand the uses of LST data and considered how current limitations may steer future developments. The final report for this workshop is available at http://rain.atmos.colostate.edu/GRP/reports/NCDC-LSTWorkshopReport_final.pdf.

The structure of the workshop was a mixture of oral and poster presentations together with breakout sessions. As part of the agenda participants were invited to complete a LST questionnaire. The summary findings of the questionnaire are presented in section 4.2. As a baseline, the workshop used the "NASA White Paper for LST and Emissivity Needs" document compiled by Simon Hook (lead author) and 44 co-authors in May 2006. It is available at http://lcluc.umd.edu/Documents/land-esdr.asp and describes the state of the science of TIR remote sensing of LST and identifies the user communities of LST and their requirements for the products.

In addition, a document specific to the water management community, "Progress on utilizing space borne high resolution thermal radiometer in water resources research and management", and available at http://www.idwr.idaho.gov/GeographicInfo/Landsat/PDFs/european-thermal_use.pdf, was also used in the workshop. Here we recap some of the key messages from the workshop. We start by summarising the general requirements for different applications as identified in the NASA White Paper (Table 1).

*Table 1: LST and emissivity product requirements, and current TIR sources. Reproduced from the NASA White Paper for LST and Emissivity Needs.*

| Subproduct | Spatial resolution | Temporal resolution | Accuracy | Precision | Current data sources | Future data sources |
|---|---|---|---|---|---|---|
| Global | 10 – 20 km | Hourly | 0.5 K | 0.1 – 0.3 K | AIRS<br>GOES<br>MSG | CrIS<br>GOES<br>MSG |
| Regional | 1 – 5 km | 2 – 4 times daily | 0.5 – 1.0 K | 0.1 – 0.3 K | (A)ATSR<br>AVHRR<br>MODIS | (A)ATSR<br>AVHRR<br>VIIRS |
| Local | 30 – 100 m | Once every 8 – 16 days | 0.5 – 1.0 K | 0.1 – 0.3 K | ASTER<br>Landsat | |
| Emissivity | 1% or better (in 8 - 12.5μm) and 3% or better (in 3.6 - 4.2μm) all resolutions | | | | | |

Using these requirements as a basis for discussions, several limitations to the use of LST within the applications domain were identified. Firstly, most operational systems currently rely on air temperature as opposed to LST to provide information about the surface energy balance. This is due to the LST development community not issuing sufficient evaluation and demonstration of the ability of LST to provide enhanced information. It is often useful for an application to have access to both air temperature and LST, and the relationship between these needs to be better understood.

Secondly, to better understand small-scale heterogeneity and the wavelength dependence of surface emissivity as a function of surface properties, enhanced information on other properties of the land are a necessity. Progress could be made if both infrared and microwave instruments, and high and low resolution measurements, are amalgamated.

Thirdly, with respect to applications which utilise models, one challenge is that LST from EO products provides the "skin" temperature in a thin layer, whereas the LST in models can be a mixture of temperatures of thicker layers. In addition, satellite-derived LST products are biased towards clear-sky conditions, whereas models estimate LST under all-sky conditions. It is therefore beneficial to have a continuous satellite-derived LST dataset with an associated cloud mask provided. Uncertainty estimates derived for each observation would also be useful, as would sub-daily observations due to the large amplitude of the diurnal cycle.

Finally, workshop participants concluded that it would be more useful for the user community to have access to temporal variations of LST than instantaneous observations. More importantly though higher LST product accuracy is preferred to high temporal frequency. A summary of the main challenges associated with the use of LST products for applications as agreed by participants are be listed as follows:

- Limited number of products available, with only a few of these being operational;
- Difficult to ascertain exactly what is available, with no comprehensive catalogue of all products;
- The majority of products are insufficiently validated;
- Many of the products are discontinuous in space and time, with dichotomy between the spatial and temporal resolutions;
- Insufficiently long term records, with these often being sensor or algorithm specific.

A compilation of the various user application requirements for spatial and temporal resolution of TIR imagery is provided in Table 2.

*Table 2: Applications and associated LST spatial and temporal target resolutions. Reproduced from the NCDC Workshop Report.*

| **Application** | **Target spatial resolution (m)** | **Target temporal resolution** | **Specific requirements** |
|---|---|---|---|
| Climate change | 5000 | 1 – 3 hrs | Sensor overlap |
| Climate change – urban heat island | 50 | 12 hrs – 30 days | Diurnal range |
| Land/atmosphere feedbacks – soil moisture | 50 | 12 hrs – 7 days | Single observation near maximum temperature or diurnal range |
| Modelling studies – numerical weather prediction | 1000 | 1 – 3 hrs | |
| Land cover change – land use | 50 | 12 hrs – 30 days | Diurnal range |
| Crop management – agricultural yield and water use | 50 | 1 – 7 days | Co-located vegetation cover |
| Water management – national drought assessment | 1000 | 1 hr | Co-located vegetation cover |
| Water management – regional drought monitoring | 50 | 1 – 7 days | Co-located vegetation cover |
| Water management – watersheds and ecological services | 50 | 1 – 7 days | |
| Fire monitoring | 50 | 12 hrs – 7 days | Sensitivity to high temperatures |
| Geological applications – lithology and geological hazards | 50 | 12 hrs – 7 days | Sensitivity to high temperatures and diurnal range |

Although many of the current and future satellite platforms will not meet these requirements, they illustrate the needs of the LST community. Furthermore, the water management document identified more specific user requirements for this community. They include the following:

- Multiple observation angles to derive the surface temperatures of plant leaves and soil separately;
- Multiple TIR channels to aid atmospheric correction;
- A TIR pixel size of 30 to 90 m to adequately resolve fields;
- An overpass time between 10:00 and 14:00 to capture highest evapotranspiration rates;
- A combination of LST imagery from different TIR satellites to reduce the large time gap between successive cloud free images;
- Collocated multispectral observations to characterize vegetation and the full energy balance;
- A minimum revisit time of one week at high resolution, and once/twice daily coverage at coarser resolutions.

### *4.2. NCDC LST user questionnaire*

A total of twenty-one participants took part in this user survey, some actively involved in more than one field. Ten participants were involved in LST product development, five were involved in LST modelling, eleven were users of satellite-derived LST data, and three were involved in validation. The participants included individuals who were members of teams that have been involved in the development of LST product, which included MODIS, AATSR, AVHRR and SEVIRI, but also datasets combining GOES and MODIS, and ISCCP and GOES. Pertinent questions and responses have been summarised here.

Q. What are the main limitations of the current LST products available to the community?

R. Responses included:

- Poor accuracy and precision
- The accuracy claimed for products is often better than the difference between different products (limits confidence in existing products)
- Limited availability of some products

- Cloud contamination
- Revisit time vs. spatial resolution
- Lack of validated products and difficulty of validation exercises
- Limited number of validation ground observations
- Inconsistency between products, with a greater number of intercomparison studies with other estimates from models, remote sensing and in situ data being required
- Poor reliability
- Angular dependency (directional character of products)
- Algorithm dependency
- Inadequate spatial resolution (need less than 100 m for local/regional applications)
- Inadequate temporal resolution (need 5-10 days revisit)
- Emissivity uncertainty
- Lack of long term datasets with moderate resolution
- Limited number of operational products
- Use of old/non-standard formats
- Use of different algorithms
- Lack of products that resolve the diurnal cycle
- Lack of products for all sky conditions
- Lack of estimates under clouds
- Unresolved spatial heterogeneity in complex topography /mountainous regions.

Q. What are the ideal characteristics of an LST product that would match your needs?

R. Although the specifications for accuracy, precision and uncertainty, as well as spatial and temporal resolution varied considerably between users, there was a general consensus that data projections should include UTM and geographical latitude and longitude. Furthermore, HDF, NetCDF and binary formats should all be made available. Although some users preferred swath data, the vast majority of users indicated their preference for gridded data, with data aggregation to regional and national scales considered useful. Finally, the resolving of the LST diurnal cycle was a unanimous request.

Q. What are your main concerns regarding the LST products that will/will not become available in the future (next 10 years)?

R. Although users were optimistic regarding potential opportunities of datasets based on a combination of polar orbiting and geostationary retrievals, and the feasibility of multi-sensor multi-platform LST products, concerns included:

- Lack of longevity and consistency of products
- Lack of adequate cover of diurnal cycle
- Lack of intercalibrated data from satellite to satellite to get uniform long term global data
- Inadequate spatial resolution (high resolution required)
- Limited availability of products
- Existence of systematic biases in products
- Lack of consistency of instrument or spectral channels across platforms
- Inadequate accuracy to meet user needs
- Most products are clear-sky biased
- Inadequate cloud mask.

Q. As a user of LST products, how much interaction, and what type (e.g., collaboration, clarification through literature only, data center contacts), do you have with the LST product development community (none, some, a lot)?

R. The general consensus was that little or no interaction was experienced with the product development community. Only a few users acknowledged any interaction with product developers, primarily through literature search and contact with data centres. Direct contact with individuals tended to be limited to conferences and workshops. There were some requests for more workshops to be held which bring together the development and user communities.

Q. Based on your experience and applications, what is the critical metadata and QA information needed in LST products?

R. For model-derived LST datasets requirements included geolocation information, details of the models themselves, and details regarding both the atmospheric forcing data details and the formulations of the atmospheric boundary layer. For in-situ LST data, primary requirements also included geolocation information; but also timing of acquisitions; and information regarding the instruments used, such as precision, and calibration; with the importance of accuracy and precision being stressed. Ancillary data such as surface fluxes and meteorological conditions, including cloud information, and emissivity values used were also highlighted. Finally, requests were made for the radiometric skin temperatures and the downwelling radiance measured. For satellite-derived LST products responses have been summarised as follows:

- Cloud mask and error estimates for cloudy pixels
- Product accuracy and precision, and error bars
- Pixel geolocation information
- Observation and illumination geometries
- Exact acquisition time
- Type of instrument, instrument error, and instrument precision
- Calibration information (including coefficients)
- Radiance statistics
- Transmissivity
- Adopted emissivity
- Algorithm details and assumptions regarding atmosphere
- Surface classification
- Original resolution of data
- Quality flags
- Satellite ID.

Q. Which type of product do you tend to consider more useful?

R. Fifteen respondents considered a continuous product in space more useful, where LST estimates are created for all pixels (clear and cloudy) accompanied by a separate cloud mask. Whereas only three respondents preferred a discontinuous product in space more useful, in which LST estimates are only produced for pixels identified as cloud free with a given level of confidence.

# 5. Current user survey

## 5.1. LST users

The main focus of this exploitation document is to report on canvassed opinion in this study regarding LST datasets derived from EO satellites. A questionnaire was devised to extract information on the current uses of LST data in research activities and what limitations have been encountered. The questionnaire was sent to leading scientists primarily based in the European Community, with selected individuals from the US also approached. The respondents are identified in table 3, with responses to the individual questions summarized in table 4. These were analyzed further in order to extract some common themes.

In addition to their previous and current use of LST data, respondents were invited to comment on difficulties encountered while using the current suite of LST products, and what changes, if any, they would like to see implemented in future developments. A full breakdown of the questions that were posed is listed as follows:

**1.** What is your chief current or potential application for surface temperature data (e.g. model, analysis, process studies or other applications)?

**2.** Which land surface temperature (LST) datasets have you used?

**3.** What made you choose this/these particular LST product(s)?

**4.** Do you have any future plans for using LST data, and if so, what are they?

**5.** What limitations, if any, do you consider exist with satellite-derived LST products? How useful is below-cloud LST, e.g., from microwave instruments, or designation of hot pixels, e.g. pixels from saturated scenes (surface temperature very high).

**6.** What spatial and temporal resolutions are appropriate to your application

**7.** What changes, if any, would you find useful for your future use of satellite-derived LST data?

**8.** Please add a sample list of publications relevant to LST.

*Table 3: Questionnaire participants.*

| User | Affiliation | Research interests |
|---|---|---|
| Elizabeth Good | Met Office, Exeter, UK | Development and validation; energy fluxes and air temperature |
| Frank Goettshe | KIT, Germany | Development and validation; diurnal cycles; land cover mapping |
| Folke Olesen | KIT, Germany | Diurnal cycles; land cover mapping |
| Simon Hook | NASA JPL | Development and validation; climate change monitoring |
| Isobel Trigo | LandSAF group | Development and validation; LST intercomparison |
| Chris Taylor | CEH, Wallingford, UK | Evapotranspiration and rainfall; Drought stress; soil moisture retrievals |
| Josh Fisher | NASA JPL | LST intercomparison |
| Martin de Kauwe | CEH, Wallingford, UK | Evapotranspiration and rainfall |
| Mark McCarthy | Met Office, Exeter, UK | Urban heat island |
| Emilio Chuvieco | UAH, Spain | Burned area mapping; fuel moisture derivation |
| John Edwards | Met Office, Exeter, UK | Model validation |
| Catherine Prigent / Carlos Jimenez | CNRS Observatoire de Paris | Development and validation; LST intercomparison |
| Bill Kustas / Martha Anderson | USDA-ARS | Evapotranspiration; surface energy balance; drought stress; evapotranspiration |
| Bob Su | University of Twente, Netherlands | Surface energy balance; drought stress |
| Benedicte Dousset | University of Hawaii | Urban heat island |
| Massimo Menenti | Delft University, Netherlands | Energy and water fluxes; data assimilation; drought stress; irrigation |

### 5.2. *Results*

*Table 4: Summary of survey feedback; each column represents questions 1-7 and each row represents brief accounts of the responses of every respondent.*

| | | | Questions | | | |
|---|---|---|---|---|---|---|
| **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| Monitoring surface temperatures | SEVIRI, AATSR, MODIS, METOP/AVHRR | Temporal resolution; accessibility; spatial resolution | Monitoring surface temperatures during heat waves | Cloud contamination and misidentification; accuracy; error information; low spatial resolution (microwave) | Spatial: 1km; 5-10km | Error information; condensed products; Level-3 products |
| Diurnal cycles; product validation | SEVIRI, MODIS, NOAA/AVHRR | Consistency; long-term availability; quality | Product validation | Accessibility; error information; emissivity information; insufficient validation | Spatial: 1km Temporal: 4 times daily | Emissivity information; error information; increased validation |
| Diurnal cycles; change detection | SEVIRI, MODIS, AATSR, NOAA/AVHRR | Cross-comparison | Product validation | Accuracy; cloud misidentification | Temporal: 15 minute | Correction of view angle dependency |
| Product calibration / validation | ASTER, MODIS, Landsat, NOAA/AVHRR, MTI | Spatial and temporal resolution | Product calibration / validation; climate analysis | Split-window algorithms; signal saturation; low spatial resolution (microwave) | Spatial: 1km / <100m Temporal: daily / weekly | Common LST algorithms; additional channels |
| Algorithm development | SEVIRI, MODIS, AATSR | Documentation; accessibility | Product validation; model validation | Cloud contamination; low spatial resolution (microwave); view angle dependency | Spatial: >500m / <5km Temporal: full diurnal cycle | Emissivity information; improved cloud screening; correction of view angle dependency |
| Land-atmosphere coupling; model validation | SEVIRI, MODIS | Temporal resolution; long-term availability | Land-atmosphere coupling; model validation; use of long-term (A)ATSR | Cloud contamination; cloud misidentification | Spatial: 1km | Improved cloud screening |
| Intercomparison studies | MODIS | Spatial resolution; long-term availability | None | Emissivity information | Spatial: High Temporal: High | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Land-atmosphere coupling | SEVIRI | Temporal resolution | None | Cloud misidentification; emissivity and land cover assumptions | Temporal: 15-30 minutes | Uncertainty characterisation |
| Urban heat islands | AATSR, MODIS | Accessibility; spatial resolution; long-term availability | Urban heat islands; model validation | Emissivity assumptions | Spatial: 1km Temporal: daily | Near real-time provision of LST |
| Fire monitoring | NOAA/AVHRR, MODIS | AVHRR receiving station | Fire monitoring | - | Temporal: <1 hour / >6 hours | Emissivity information; increased validation |
| Model validation | SEVIRI, GOES/Imager | Temporal resolution | Model validation; data assimilation | Accuracy; cloud contamination and misidentification | Spatial: 1-25km Temporal: 15 minute | - |
| IR and microwave LST analysis | ISCCP, MODIS, SEVIRI | Global coverage; long-term availability; temporal resolution | Climate analysis; data assimilation | Cloud contamination | Spatial: 10-20km | Increased validation |
| Evapotranspiration; crop studies; drought studies | Landsat, ASTER, GOES/Imager, SEVIRI, MODIS, NOAA/AVHRR | Spatial resolution; long-term availability | Global modelling | Cloud contamination; low spatial resolution (IR and microwave) | Spatial: 5km / <100m Temporal: 15-30 minutes / 3-5 days | Improved data accessibility; increased resolution |
| Land-atmosphere coupling | MODIS, AATSR, NOAA/AVHRR, Landsat | Long-term availability | Land-atmosphere coupling; education | Spatial and temporal resolution; cloud contamination | Spatial: 1km / <100m Temporal: daily | Increased resolution |
| Urban heat islands | SEVIRI, NOAA/AVHRR, AATSR, MODIS, Landsat, ASTER | Spatial and temporal resolution | Land-surface climatology | Spatial and temporal resolution | Spatial: 10m - 100km | Increased resolution |
| Crop studies; drought studies | NASA/HCMM, Landsat, SEVIRI, MODIS, (A)ATSR, ASTER, NOAA/AVHRR | Product evolution | Land-surface climatology; drought early warning | Low spatial resolution (microwave); signal saturation | Spatial: 50m / 1-5km | Bi-angular retrievals (AATSR) |

The LST user community is actively involved in the development, validation, and application of LST data from a wide range of satellite instruments, both infrared and microwave. In the context of this survey the vast majority of respondents have only used LST derived from infrared channels, for the most part stating the very low resolution of passive microwave sensors as the principle reason for not taking greater advantage of this data stream. A couple of users have however investigated the use of microwave data to bridge the gaps due to cloud contamination.

Although the user survey produced a large amount of information representing the opinions of the scientific community some general observations can be ascertained. Firstly, the choice of LST product utilised for a given application is governed by several factors. Secondly, no single product is able to satisfy all the requirements of the user community; instead data from multiple sources is often utilised in any one application. Finally, although the current family of LST products together may satisfy many needs of the user community several important limitations were highlighted, which may be a restriction to the wider use of these products. Some of these limitations focus on the various technical constraints, but a few are concerned with more administrative constraints, such as data accessibility and documentation quality.

Considering product selection first, a number of recurring themes were evident from the survey. Availability of data and the spatial/temporal resolution dichotomy appear to be strong drivers as to the choice of dataset utilised for an application, and were the most widely cited reasons in the survey. For instance, LST products derived from geostationary satellites have primarily been used for regional studies where the full diurnal cycle is required. For local studies though, such as urban heat island investigations, the spatial resolution of geostationary instruments is deemed too low. Where longer time-series have been required MODIS and AVHRR data have been the products of choice, whereas ATSR data has tended to be used for cross-comparison rather than as the primary source of LST information.

Other explanative reasons include the ease of accessibility and the quality of the accompanying documentation; this encompassed both the user guides and quality and quantity of related scientific publications. With regards to the user perception of data availability, some datasets are considered to be less accessible than others. For instance, ATSR data was viewed by more than one respondent as being more difficult to access than MODIS or SEVIRI data. This may limit its use by the research community, as was suggested in the survey, and is an issue that should be addressed. Finally, data quality was also mentioned as a reason for product choice.

In respect to this latter point, there was an overwhelming consensus for improved accuracy of products, with a particular emphasis on cloud clearing apparent. Where cloud is viewed as a problematic constraint with infrared radiometry, for the most part the use of microwave retrievals is perceived to deliver too coarse a resolution to offer a feasible alternative. In addition to improved cloud masking, accounting for aerosols such as dust and the products of biomass burning, which scatter and absorb radiation, was also raised as an important consideration; one which has been insufficiently addressed. Where accuracies have been quoted they are often found to be optimistic, with the use of split-window algorithms considered by more than one respondent as being limited in their assumptions leading to reduced accuracy.

Expanding on this need for improved accuracy, what also emerged from this survey is the need for a concerted effort in validating products. Current validation of products is viewed by many as being insufficient, being limited to specific sites or over limited time periods, whereby several biomes remain, for the most part, without any validation study. This reduces the confidence in a product when utilised at the global scale over long periods.

While spatial and temporal resolutions offered by the current crop of LST products was perceived by some respondents as being restrictive, this tended to be application related. For example, users involved in local studies, such as those investigating agricultural fields or urban heat islands, tend to consider the development of high spatial resolution LST datasets to be most important; whereas users involved in regional or global modelling tend to consider the availability of data to map the full diurnal cycle to be preferable.

When respondents were canvassed as to their opinions on future changes to LST products, naturally the desire to have very high spatial resolution data (<100m) was prevalent amongst the users sampled. This was particularly evident for users concerned with highly heterogeneous environments. Reduced duration between revisits was also stated as a preference amongst several respondents, with the potential of satellite constellations to ensure sub-daily acquisitions being one suggestion. Beyond this, there were a couple of other key requirements for future satellite-derived data which were shared by several respondents. Firstly, characterisation of the uncertainty of a product; this is important for several reasons, including model validation and data assimilation into models. Secondly, the provision of emissivity estimates; this is deemed useful in a number of applications, for instance in local studies where the surface is highly heterogeneous such as the urban environment.

Although model validation and data assimilation has only previously been investigated by a small proportion of the respondents, this is envisaged to increase in the future. Indeed, the amalgamation of model and EO data is currently receiving much attention as modellers attempt to overcome various limitations in the models by integrating observational data. This adds a different perspective to the requirements a LST product must meet. For instance, the availability of long-term datasets becomes especially pertinent for comparing the output of models over several years. As for data assimilation, accurate assessment of observational uncertainty is paramount to the performance of the various assimilation mechanisms. Such requirements indicate an increase in validation studies is needed.

Other prominent suggestions include moving to retrieval based on three thermal channels, bi-angular retrievals of LST from (A)ATSR, correcting for view angle dependency, and a re-configuration of the information provided within a product. It was noted that users of the operational data may be deterred from particular products due to the large amounts of data encompassed within a product file, most of which although useful for research and diagnosis may not be required by many users. In addition, such product files can take a long time to download occupying vast quantities of storage space. Indeed, for a number of applications, such as climate modelling, the provision of level-3 products (for example daily global LST at 0.5°) are often more useful than 1km level-2 products. Few level-3 products currently exist; and ones generated from a combination of geostationary and polar-orbiting retrievals may be even more appealing to the user community.

A caveat to these limitations and recommendations is that in some cases progress is being made to address weaknesses in current LST products. For example, the ATSR product was noted by one respondent as being limited due to its use of 10km biome classification for deriving 1km LST data. This limitation is being addressed as part of the "Long Term Land Surface Temperature Validation" project.

## 5.3. *Summary*

An analysis of the feedback from both the survey conducted as part of this project and that carried out as part of the NCDC workshop reveals a number of common threads. Here we summarise these as a succinct list of the most important requirements as perceived by the users which may enhance the exploitation of satellite-derived LST products.

The current batch of operational LST products is subject to a number of limitations. The most widely cited of these fall into four broad categories:

- Accuracy – Uncertainties include those associated with emissivity and land cover classifications, but perhaps most significantly inadequate cloud screening. Indeed, even where cloud is correctly identified the lack of LST estimates below clouds is perceived as a limitation, with microwave retrievals not offering a feasible alternative at sufficiently high spatial resolution.
- Availability – Currently only a few operational LST products are available, with no single source of information as to what products are available and the data they offer. Not all products share the same ease and openness of accessibility, with data made available in different file formats and accompanied by a variety of metadata. In some cases the sheer quantity of metadata might seem a deterrent to a wider utilisation of satellite-derived LST products by the scientific community. Many LST products also do not offer sufficiently long-term records. Furthermore, a time series of LST derived from EO may be sensor or algorithm specific. Where there does exist the potential for a long-term record, this is not always being exploited.
- Resolution – The dichotomy between the spatial and temporal resolutions of satellite instruments tends to be more application specific. For local applications very high spatial resolution are sometimes required with no current LST product able to meet this requirement. For many applications the resolution of the full diurnal cycle is a necessary requirement.
- Validation - LST products remain insufficiently validated. There are several reasons for this including the difficulty of carrying out validation exercises, the limited number of validation ground observations, the specificity of the sites, and the limited time periods over which validation is carried out. This leads to inconsistencies between LST products.

The opinions of the user community have been collated in this report as to what changes would be beneficial to overcome the limitations highlighted. Under the same broad categories we can summarise them as follows:

- Accuracy – Improved cloud screening algorithms, and accounting for aerosols are required. Multiple observation angles and thermal channels are recommended to improve atmospheric correction. Uncertainty is however unavoidable, so a provision of uncertainty estimates is important.
- Availability – Data should be more readily accessible with the provision of slimmed down products consisting of the most important fields; the consensus of the user community would indicate these to be latitude, longitude, time, and LST error in addition to the LST field. In addition to the provision of level-2 data, an increase in the provision of level-3 gridded data at either a variety of resolutions (0.5°, 1.0° for example) or tiled by biome, which is often more useful in some applications, is recommended. The processing of long time-series of LST is also a priority. Good documentation and commonly used file formats are important to ensure potential exploitation of LST products is satisfied. Finally, a greater dialogue between the user community and the product development community is called for.
- Resolution – To adequately resolve agricultural fields and urban features pixel sizes less than 100m are suggested, with revisit times of one week of less for such high resolution. A better resolution of the LST diurnal cycle was called for, with constellations of instruments to reduce the gaps between successive cloud free images a suggestion. It may be that combined LST products from instruments on Low Earth Orbit (LEO) satellites and geostationary satellites would be able to resolve the diurnal cycle of LST at a global scale.
- Validation – An increased emphasis on validation is a priority. This includes both the undertaking of longer validation studies over a variety of surface regimes, but also an increase in the number of intercomparison studies.

While some of these changes must wait for future missions there is scope for implementing changes with respect to the current suite of LST products. A greater emphasis is called for with regards to increasing the number of validation studies, and improving the accuracy of operational products. What is more, to increase the exploitation of satellite-derived LST products they need to be well documented, straightforward to access, and user-friendly in terms of the quantity and format of the data and accompanying metadata.

This report is based on the opinions of a sample of the LST user population, and while it is expected that the majority of the important opinions have been recorded it is possible that other considerations exist within the user community which were not sampled here.

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